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Research report

Simple gaze analysis and special design of a virtual Morris water maze provides a new method for differentiating egocentric and allocentric navigational strategy choice

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ABSTRACT

We present a novel method of combining eye tracking with specially designed virtual environments to provide objective evidence of navigational strategy selection. A simple, inexpensive video camera with an easily built infrared LED array is used to capture eye movements at 60 Hz. Simple algorithms analyze gaze position at the start of each virtual maze trial to identify stimuli used for navigational orientation. To validate the methodology, human participants were tested in two virtual environments which differed with respect to features usable for navigation and which forced participants to use one or another of two well-known navigational strategies. Because the environmental features for the two kinds of navigation were clustered in different regions of the environment (and the video display), a simple analysis of gaze-position during the first (i.e., orienting) second of each trial revealed which features were being attended to, and therefore, which navigational strategy was about to be employed on the upcoming trial.

1. Introduction

A key problem in the study of human navigational behavior is the difficulty researchers have in discerning the strategies that participants use to complete navigation tasks [1]. There appear to be a variety of types of cognitive processing that can be classified into one of two distinct strategies for navigation. The first of these relies on the acquisition of simple stimulus–response associations between environmental stimuli and body-based responses such as “go towards this object” or “turn right at the corner” [2]. The second is “cognitive mapping” [3], the process of forming an internal representation of the environment.

The two types of cognitive processing underlying spatial navigation have come to be classified as egocentric and allocentric [4]. Egocentric navigation consists of executing stimulus–response associations between individual landmarks (environmental features) and body-based responses until an interim or final goal is reached. Egocentric navigational strategies (sometimes called non-spatial [1], or simple [5]) do not require knowledge of the relations among environmental stimuli. In contrast, allocentric navigation (sometimes called spatial [1,6]) consists of moving in distances and directions according to vectors computed to lie between the navigator’s current position and the destination [7]. These computations are based on a cognitive map which incorporates the spatial relations among landmarks in the environment as well as their relationship to the target destination. The “gold standard” for testing allocentric navigation is the Morris water maze (MWM) [8]. This task requires rats to swim to an invisible platform placed just below the surface in a round pool of milky water. The rat completes a number of trials from different start positions around the wall of the pool, and thus has to learn the location of the platform using available cues that include the arena wall (which is a uniform texture and color) and distal room cues located outside of the pool. The ability of the rat to directly return to the platform regardless of start position is taken to mean that the rat has formed a representation (or cognitive map) of the environment [8] and is using an allocentric system to navigate.

Recently, researchers have become interested in strategy use and selection in different paradigms. In general, researchers have differentiated navigational strategies through participant self-report or by combining self-report with inferences from behavioral data [1,9,10]. However, self-report is inherently subjective and it

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[1] http://www.abvsciences.com/.

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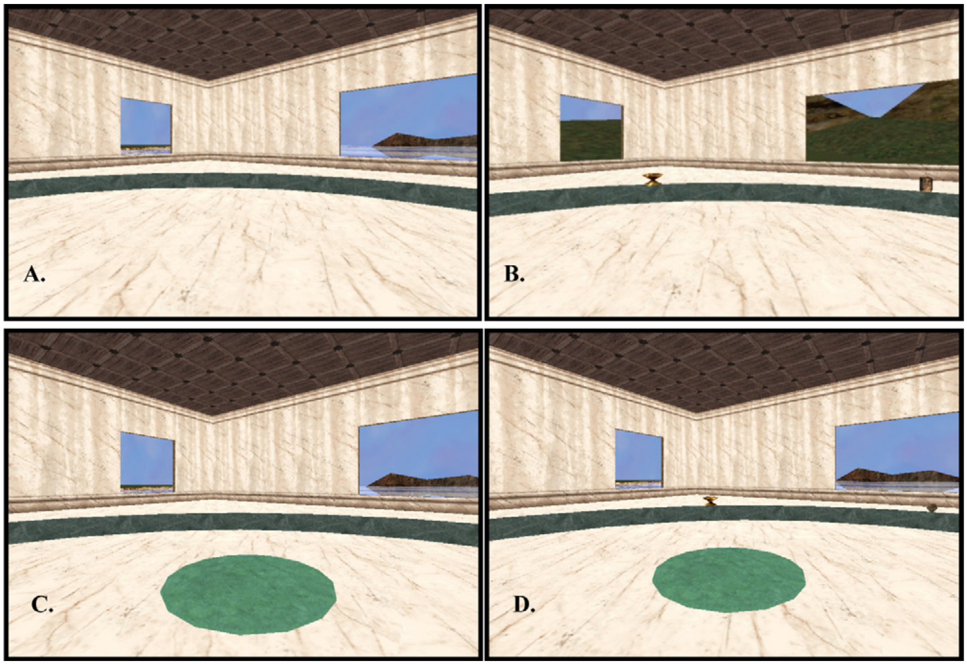

Fig. 1. Virtual environments. (A) Place maze, a virtual Morris water maze. (B) The Cue maze, a virtual landmark maze. (C) The Place maze with the platform visible in its fixed location (i.e., after the participant has stepped on it). Note that during trials, the platform's location can be identified only by a constellation of distal landmarks, forcing the participant to find it allocentrically. (D) The Cue maze with the platform visible (coincidentally) in the southeast quadrant, marked by the golden urn. Because the platform (and urn) change quadrants each trial, this proximal object provides the only means of identifying the platform location, forcing the participant to find it egocentrically.

would be beneficial to be able to identify navigational strategies in a more objective manner. Further, three studies (one animal and two human) have provided evidence that the selection of a navigational strategy (egocentric or allocentric) can be spontaneous and that the initial strategy can be switched mid-task in favor of another [1,6,9]. This is problematic for studies that assess navigational strategies only at the conclusion of testing, because animal subjects or human participants may be using more than one strategy at different times during the testing and because different strategies may lead to similar performance (see for example [11]). This use of spontaneous and variable strategy selection in response to environmental stimuli implies that in at least some navigational situations, the response to stimuli depends upon the state of the navigator. Clearly, it would be valuable to have an objective means of identifying selected strategies within a given session or even on a trial-by-trial basis.

The primary goal of the present study is to investigate the use of eye tracking as an objective, reliable method to discriminate egocentric and allocentric strategies within sessions and individuals.

The tracking of eye movements is a well-established method of analysis in psychological research. In early studies, eye movement tracking was used to record visual attention in studies of reading comprehension and selective visual attention (see for example, [12]). The increased availability of high quality eye tracking equipment has now made it possible to extend this research into even more applied fields (e.g., [13–15]). Eye-tracking has also been applied to studies of spatial cognition, but to date, most have presented stimuli that consist of static images on a computer screen [16–18]. Such studies fail to take into account that navigation can cause perceived stimuli to change: they appear, disappear, or change their relation to each other as the navigator moves. In a notable exception, eye movements in a complex, moving environment were recorded but these were used only to confirm post-session verbal reports [19]. Thus, there is a need to investigate navigational strategies using eye tracking while the participant is moving through space. Virtual environments are well suited to this task, but there are challenges to overcome.

The main difficulty with tracking eye movements in response to a dynamic, virtual environment is the sheer volume of data generated because the relation between gaze position and environmental features must be computed for each frame, and there can be up to 30 frames/s. In the past, such data analysis has been extremely labor intensive, leading to secondary problems with selection of data for analysis. For example, El-Nasr and Yan [20] investigated visual attention while participants played a complex three-dimensional video game. Analysis was accomplished manually using frame-by-frame extraction of coordinates. Due to this lengthy process, only six participants could be tested so generalization becomes problematic, and group studies using this method would be difficult. One approach used in the study of newspaper-reading overcomes this problem by organizing the computer presentation screens into discrete segments containing specific types of information (binning) [21]. This approach has the advantage of limiting the volume of data by measuring a percentage of gaze dwell time in a select area. So although the image presented on the screen is moving dynamically, researchers can still calculate the length of time participants spend looking at particular regions of the screen. This compliments studies of navigational strategy selection since areas of interest can be linked to allocentric and egocentric stimuli in a virtual environment. Recently we demonstrated that analysis of eye movements during orientation at the start of trials in an allocentric virtual MWM can be used to identify, trial-by-trial, participants' tendency to orient themselves to their location in space using an allocentric strategy [22].

This present article presents a method of discriminating between egocentric and allocentric navigation strategies on a trial-by-trial basis using eye tracking in a specially designed virtual MWM. There are two critical design features of the virtual maze used here. The first consists of a vertical separation of allocentric stimuli from other stimuli within the environment. That is, all distal features that can be used by the participant to establish their position in the maze are located above a horizon, and remain above that horizon regardless of where the participant is in the maze. The second important design feature was the adaptation of our standard